



Study of CP -Violating Asymmetries in $B^0 \rightarrow \pi^+ \pi^-$ Decays

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Abstract

We present a measurement of CP -violating asymmetries in $B^0 \rightarrow \pi^+\pi^-$ decays based on a 41.8 fb^{-1} data sample collected at the $\Upsilon(4S)$ resonance with the Belle detector at the KEKB asymmetric-energy e^+e^- collider. We fully reconstruct one neutral B meson as a $B^0 \rightarrow \pi^+\pi^-$ CP eigenstate and identify the flavor of the accompanying B meson from its decay products. From the asymmetry in the distribution of the time intervals between the two B meson decay points, we obtain the CP -violating asymmetry parameters $\mathcal{S}_{\pi\pi} = -1.21^{+0.38}_{-0.27}(\text{stat})^{+0.16}_{-0.13}(\text{syst})$ and $\mathcal{A}_{\pi\pi} = +0.94^{+0.25}_{-0.31}(\text{stat}) \pm 0.09(\text{syst})$.

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Kobayashi and Maskawa (KM) proposed, in 1973, a model where CP violation is incorporated as an irreducible complex phase in the weak-interaction quark mixing matrix [1]. Recent measurements of the CP -violating parameter $\sin 2\phi_1$ by the Belle [2] and BaBar [3] collaborations established CP violation in the neutral B meson system that is consistent with KM expectations. Measurements of other CP -violating parameters provide important tests of the KM model. In this Letter we describe a measurement of CP -violating asymmetries in the mode $B^0 \rightarrow \pi^+\pi^-$ [4]; these are sensitive to the parameter $\sin 2\phi_2$ [5].

The KM model predicts CP -violating asymmetries in the time-dependent rates for B^0 and \bar{B}^0 decays to a common CP eigenstate, f_{CP} [6]. In the decay chain $\Upsilon(4S) \rightarrow B^0\bar{B}^0 \rightarrow f_{CP}f_{\text{tag}}$, where one of B mesons decays at time t_{CP} to f_{CP} and the other decays at time t_{tag} to a final state f_{tag} that distinguishes between B^0 and \bar{B}^0 , the decay rate has a time dependence given by [7]

$$\mathcal{P}_{\pi\pi}^q(\Delta t) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} [1 + q \cdot \{\mathcal{S}_{\pi\pi} \sin(\Delta m_d \Delta t) + \mathcal{A}_{\pi\pi} \cos(\Delta m_d \Delta t)\}], \quad (1)$$

where τ_{B^0} is the B^0 lifetime, Δm_d is the mass difference between the two B^0 mass eigenstates, $\Delta t = t_{CP} - t_{\text{tag}}$, and the b -flavor charge $q = +1$ (-1) when the tagging B meson is a B^0 (\bar{B}^0). The CP -violating parameters $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ defined in Eq. (1) are expressed by $\mathcal{S}_{\pi\pi} = 2\text{Im}\lambda/(|\lambda|^2 + 1)$ and $\mathcal{A}_{\pi\pi} = (|\lambda|^2 - 1)/(|\lambda|^2 + 1)$, where λ is a complex parameter that depends on both $B^0\bar{B}^0$ mixing and on the amplitudes for B^0 and \bar{B}^0 decay to $\pi^+\pi^-$. In the SM, to a good approximation, $|\lambda|$ is equal to the absolute value of the ratio of the \bar{B}^0 to B^0 decay amplitudes. We would have $\mathcal{S}_{\pi\pi} = \sin 2\phi_2$ and $\mathcal{A}_{\pi\pi} = 0$, or equivalently $|\lambda| = 1$, if the $b \rightarrow u$ tree amplitude were dominant. The situation is complicated by the possibility of significant contributions from gluonic $b \rightarrow d$ penguin amplitudes that have a different weak phase and additional strong phases [8]. As a result, $\mathcal{S}_{\pi\pi}$ may not be equal to $\sin 2\phi_2$ and direct CP violation, $\mathcal{A}_{\pi\pi} \neq 0$, may occur.

This measurement is based on a 41.8 fb $^{-1}$ data sample, which contains 44.8 million $B\bar{B}$ pairs, collected with the Belle detector at the KEKB asymmetric-energy e^+e^- (3.5 on 8 GeV) collider [9] operating at the $\Upsilon(4S)$ resonance. At KEKB, the $\Upsilon(4S)$ is produced with a Lorentz boost of $\beta\gamma = 0.425$ nearly along the electron beamline (z). Since the B^0 and \bar{B}^0 mesons are approximately at rest in the $\Upsilon(4S)$ center-of-mass system (cms), Δt can be determined from the displacement in z between the f_{CP} and f_{tag} decay vertices: $\Delta t \simeq (z_{CP} - z_{\text{tag}})/\beta\gamma c \equiv \Delta z/\beta\gamma c$.

The Belle detector [10] is a large-solid-angle spectrometer that consists of a silicon vertex detector (SVD), a central drift chamber (CDC), an array of aerogel threshold Čerenkov counters (ACC), time-of-flight scintillation counters (TOF), and an electromagnetic calorimeter comprised of CsI(Tl) crystals (ECL) located inside a super-conducting solenoid coil that provides a 1.5 T magnetic field. An iron flux-return located outside of the coil is instrumented to detect K_L^0 mesons and to identify muons (KLM).

The $B^0 \rightarrow \pi^+\pi^-$ event selection is described in detail elsewhere [11]. We use oppositely charged track pairs that are positively identified as pions according to the combined information from the ACC and the CDC dE/dx measurement. Candidate B mesons are reconstructed using the energy difference $\Delta E \equiv E_B^{\text{cms}} - E_{\text{beam}}^{\text{cms}}$ and the beam-energy constrained mass $M_{\text{bc}} \equiv \sqrt{(E_{\text{beam}}^{\text{cms}})^2 - (p_B^{\text{cms}})^2}$, where $E_{\text{beam}}^{\text{cms}}$ is the cms beam energy, and E_B^{cms} and p_B^{cms} are the cms energy and momentum of the B candidate. The signal region is defined as $5.271 < M_{\text{bc}} < 5.287$ GeV/ c^2 and $|\Delta E| < 0.067$ GeV, corresponding to $\pm 3\sigma$ from the central

values. In order to suppress background from the $e^+e^- \rightarrow q\bar{q}$ continuum ($q = u, d, s, c$), we form signal and background likelihood functions, \mathcal{L}_S and \mathcal{L}_{BG} , from two variables. One is a Fisher discriminant determined from six modified Fox-Wolfram moments [12]; the other is the B flight direction in the cms, with respect to the z axis ($\cos\theta_B$). We determine \mathcal{L}_S from Monte Carlo (MC) and \mathcal{L}_{BG} from data, and require $\mathcal{L}_S/(\mathcal{L}_S + \mathcal{L}_{BG}) > 0.825$ for candidate events. Figure 1 shows the ΔE distribution for $\pi^+\pi^-$ candidates. The signal

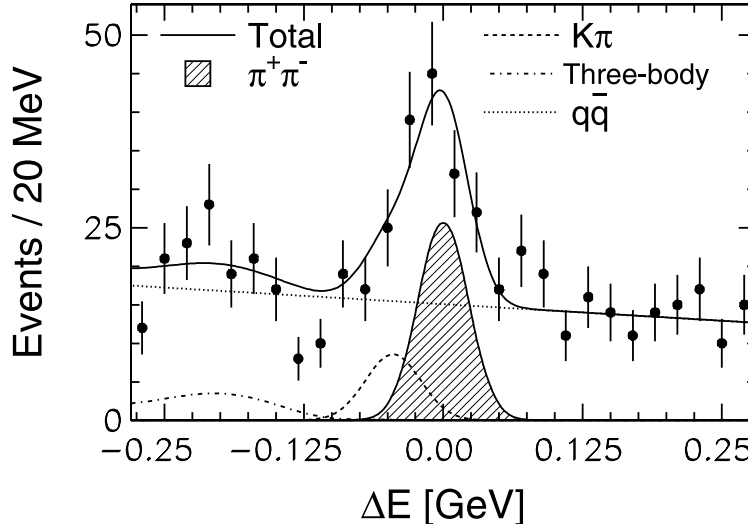


FIG. 1: ΔE distribution for $\pi^+\pi^-$ event candidates that are in the M_{bc} signal region.

yield is extracted by fitting the ΔE distribution with a Gaussian $\pi^+\pi^-$ signal function, plus contributions from misidentified $B^0 \rightarrow K^+\pi^-$ events, three-body B -decays, and continuum background. From the fit, we obtain $73.5 \pm 13.8(\text{stat})$ $\pi^+\pi^-$ events, $28.4 \pm 12.5(\text{stat})$ $K^+\pi^-$ events, and $98.7 \pm 7.0(\text{stat})$ continuum events in the signal region. The $K^+\pi^-$ contamination is consistent with the $K \rightarrow \pi$ misidentification probability measured independently. The contribution from three-body B -decays is negligibly small in the signal region.

Leptons, charged pions, and kaons that are not associated with the reconstructed $B^0 \rightarrow \pi^+\pi^-$ decay are used to identify the flavor of the accompanying B meson. We use two parameters, q and r , to represent the tagging information. The first, q , is already defined in Eq. (1). The parameter r is an event-by-event, MC-determined flavor-tagging dilution factor that ranges from $r = 0$ for no flavor discrimination to $r = 1$ for unambiguous flavor assignment. It is used only to sort data into six r intervals (boundaries at 0.25, 0.5, 0.625, 0.75 and 0.875). The wrong tag fractions for the six r intervals, w_l ($l = 1, 6$), are determined from the data; we use the same w_l values that were used for the $\sin 2\phi_1$ measurement [2].

The vertex positions for the $\pi^+\pi^-$ and f_{tag} decays are reconstructed using tracks with associated hits in the SVD. Each vertex position is also constrained by the interaction point profile smeared in the r - ϕ plane by the average transverse B meson decay length. The f_{tag} vertex is determined from all well reconstructed tracks, excluding the $B^0 \rightarrow \pi^+\pi^-$ candidate and tracks that form a K_S^0 candidate.

The proper-time interval resolution for the signal, $R_{\text{sig}}(\Delta t)$, is obtained by convolving a sum of two Gaussians (a *main* component, plus a *tail* component caused by poorly reconstructed tracks) with a function that takes into account the cms motion of the B mesons. We use the same parameters as those used for the $\sin 2\phi_1$ measurement; the fraction and

the typical width of the main Gaussian are 0.97 ± 0.02 and 1.49 ps, respectively [2]. The background resolution function $R_{q\bar{q}}(\Delta t)$, which is dominated by continuum background, has the same functional form but the parameters are obtained from a sideband region in M_{bc} and ΔE . Using these resolution functions, we perform a B^0 lifetime measurement that yields $\tau_{B^0} = 1.49 \pm 0.21(\text{stat})$ ps for $B^0 \rightarrow \pi^+\pi^-$ candidates, which is consistent with the world average value [13].

We determine CP violation parameters by performing an unbinned maximum-likelihood fit of a CP -violating probability density function (pdf) to the Δt distributions. We define the likelihood value for each event as a function of $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$:

$$P_i = \int [\{f_{\pi\pi}^l \mathcal{P}_{\pi\pi}^q(\Delta t', w_l; \mathcal{S}_{\pi\pi}, \mathcal{A}_{\pi\pi}) + f_{K\pi}^l \mathcal{P}_{K\pi}^q(\Delta t', w_l)\} \cdot R_{\text{sig}}(\Delta t_i - \Delta t') + f_{q\bar{q}}^l \mathcal{P}_{q\bar{q}}(\Delta t') \cdot R_{q\bar{q}}(\Delta t_i - \Delta t')] d\Delta t'. \quad (2)$$

Here $f_{\pi\pi}^l$, $f_{K\pi}^l$, and $f_{q\bar{q}}^l (= 1 - f_{\pi\pi}^l - f_{K\pi}^l)$ are the fractions of $\pi^+\pi^-$ signal, $K^+\pi^-$ background, and continuum background in flavor-tagging interval l , respectively. These fractions are determined on an event-by-event basis as a function of ΔE and M_{bc} , properly normalized by the average signal and background fractions in the signal region. The average fractions of $q\bar{q}$ background for six r bins ($l = 1, 6$) are 0.632, 0.505, 0.462, 0.440, 0.322 and 0.117. For higher r values where we are more sensitive to the asymmetry, the fraction of continuum background decreases; the ratio of $\pi^+\pi^-$ signal events to background $K^+\pi^-$ events is the same for all r bins. The pdfs for $\pi^+\pi^-$ ($\mathcal{P}_{\pi\pi}^q$), $K^+\pi^-$ ($\mathcal{P}_{K\pi}^q$), and continuum background ($\mathcal{P}_{q\bar{q}}$), are convolved with their respective resolution functions. We use the same vertex resolution function for $\pi^+\pi^-$ and $K^+\pi^-$ candidates. For the $\pi^+\pi^-$ signal, the pdf is given by Eq. (1) with q replaced by $q(1-2w_l)$, to account for the dilution due to wrong flavor tagging. The pdf for the $K^+\pi^-$ background is $\mathcal{P}_{K\pi}^q(\Delta t, w_l) = e^{-|\Delta t|/\tau_{B^0}}/4\tau_{B^0}\{1+q\cdot(1-2w_l)\mathcal{A}_{K\pi}\cos(\Delta m_d\Delta t)\}$, where $\mathcal{A}_{K\pi}$ is the $\bar{B}^0 \rightarrow K^-\pi^+$ and $B^0 \rightarrow K^+\pi^-$ decay rate asymmetry. We fix $\mathcal{A}_{K\pi} = 0$ [11], and τ_{B^0} and Δm_d to their world average values [13]. The pdf used for the $q\bar{q}$ background is $\mathcal{P}_{q\bar{q}}(\Delta t) = \{f_\tau e^{-|\Delta t|/\tau_{\text{bkg}}}/2\tau_{\text{bkg}} + (1-f_\tau)\delta(\Delta t)\}/2$, where f_τ is the background fraction with an effective lifetime τ_{bkg} and δ is the Dirac delta function. We determine $f_\tau = 0.011 \pm 0.004$ and $\tau_{\text{bkg}} = 2.7_{-0.7}^{+1.0}$ ps from the sideband data. In the fit, $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ are free parameters determined by maximizing the likelihood function $\mathcal{L} = \prod_i P_i$, where the product is over all $B^0 \rightarrow \pi^+\pi^-$ candidates.

The result of the fit to the 162 candidates (92 B^0 - and 70 \bar{B}^0 -tags) that remain after flavor tagging and vertex reconstruction is:

$$\begin{aligned} \mathcal{S}_{\pi\pi} &= -1.21_{-0.27}^{+0.38}(\text{stat})_{-0.13}^{+0.16}(\text{syst}); \\ \mathcal{A}_{\pi\pi} &= +0.94_{-0.31}^{+0.25}(\text{stat}) \pm 0.09(\text{syst}). \end{aligned}$$

The result is 1.3σ away from the physical boundary $\mathcal{S}_{\pi\pi}^2 + \mathcal{A}_{\pi\pi}^2 = 1$, which is consistent with a statistical fluctuation. The correlation between $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$ is found to be 0.28. In Figs. 2(a) and (b), we show the Δt distributions for B^0 - and \bar{B}^0 -tagged events together with the fit curves; the background-subtracted Δt distributions are shown in Fig. 2(c). Figure 2(d) shows the background-subtracted CP asymmetry between the B^0 - and \bar{B}^0 -tagged events as a function of Δt . The result of the fit is superimposed and shown by the solid curve.

The systematic error on $\mathcal{S}_{\pi\pi}$ is primarily due to uncertainties in the background fractions (± 0.09) and a possible fit bias near the physical boundary ($_{-0.02}^{+0.11}$). For $\mathcal{A}_{\pi\pi}$, the background fractions (± 0.06) and the wrong-tag fractions (± 0.06) are the two leading components. We

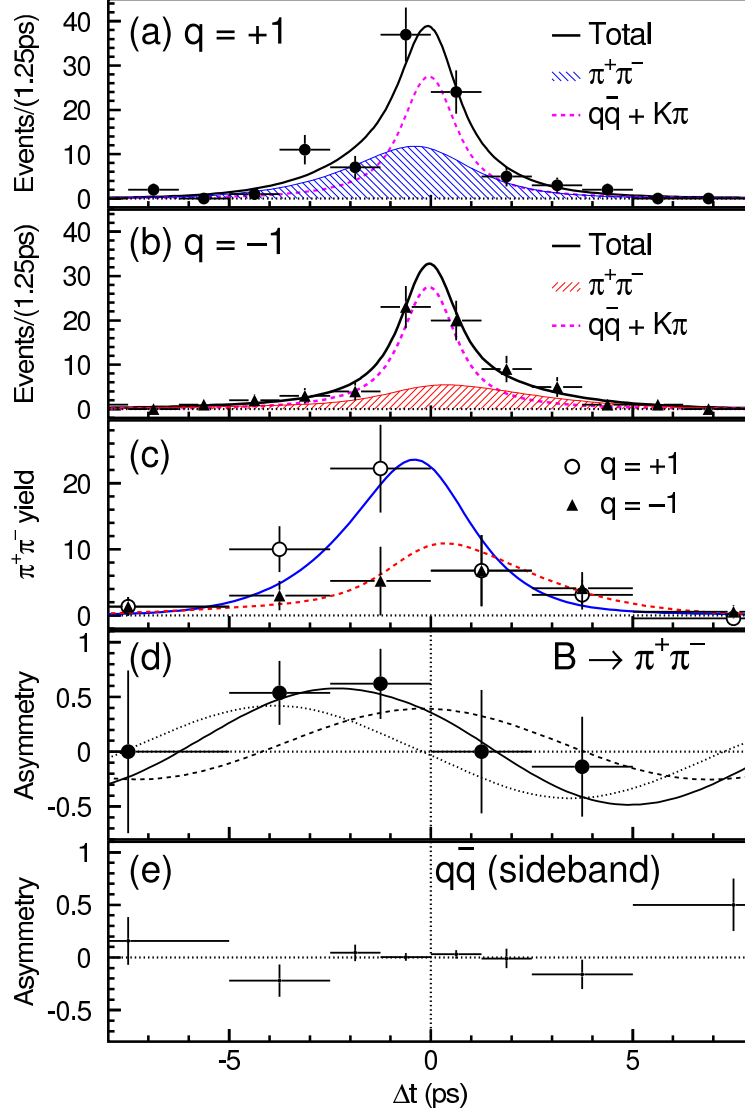


FIG. 2: The Δt distributions for the $B^0 \rightarrow \pi^+\pi^-$ candidates in the signal region: (a) candidates with $q = +1$, i.e. the tag side is identified as B^0 ; (b) candidates with $q = -1$; (c) $\pi^+\pi^-$ yields after background subtraction. The errors are statistical only and do not include the error of the subtracted background obtained by a fit. The rightmost (leftmost) bin ranges from 5 to 10 ps (-5 to -10 ps); (d) the CP asymmetry for $B^0 \rightarrow \pi^+\pi^-$ after background subtraction. The point in the rightmost bin has a large negative value that is outside of the range of the histogram; (e) the raw asymmetry for $B^0 \rightarrow \pi^+\pi^-$ sideband events. In Figs. (a) through (c), the curves show the results of the unbinned maximum likelihood fit. In Fig. (d), the solid curve shows the resultant CP asymmetry, while the dashed (dotted) curve is the contribution from the cosine (sine) term.

find that uncertainties in $f_{\pi\pi}^l$, $f_{K\pi}^l$ and $f_{q\bar{q}}^l$ in Eq. (2) account for the largest systematic errors. We add their contributions in quadrature to obtain the above values, where each contribution is obtained by varying a parameter by its error and repeating the fit. Other sources of systematic error are uncertainties in the resolution function, physics parameters (Δm_d , τ_{B^0} , and $\mathcal{A}_{K\pi}$) and the background modeling. A value of $\mathcal{A}_{K\pi} = -0.06 \pm 0.08$ is

obtained from the self-tagged $B^0 \rightarrow K^+\pi^-$ sample [11]; this introduces a systematic error of < 0.01 for $\mathcal{S}_{\pi\pi}$ and $^{+0.02}_{-0.01}$ for $\mathcal{A}_{\pi\pi}$.

We validate our fitting procedure using a large ensemble of MC pseudo-experiments wherein events are generated with nominal pdfs and the observed number of events. For various input values of $\mathcal{S}_{\pi\pi}$ and $\mathcal{A}_{\pi\pi}$, we confirm that there is no bias in the fit results. We find that the average expected errors, 0.52 for $\mathcal{S}_{\pi\pi}$ and 0.35 for $\mathcal{A}_{\pi\pi}$, are larger than our measurements. However, the probability of obtaining errors that are smaller than our measurement is 5.4% for $\mathcal{S}_{\pi\pi}$ and 23.6% for $\mathcal{A}_{\pi\pi}$; the results are within the expected range of statistical fluctuations. The measured likelihood is in good agreement with the average likelihood value obtained in the pseudo-experiments.

We perform a number of cross checks. We examine the event yields and Δt distributions for B^0 - and \bar{B}^0 -tagged events in the sideband region and find no significant asymmetry as shown in Fig. 2(e). We select $B^0 \rightarrow K^+\pi^-$ candidates, which have the same track topology as $B^0 \rightarrow \pi^+\pi^-$, by positively identifying charged kaons. A fit to 309 candidates (209 ± 16 signal events) yields $\tau_{B^0} = 1.73 \pm 0.15(\text{stat})$ ps and $\Delta m_d = 0.57 \pm 0.08(\text{stat})$ ps $^{-1}$; these are consistent with the world average values [13]. $\mathcal{A}_{K\pi}$ is 0.07 ± 0.17 , in agreement with the counting analysis mentioned above and $\mathcal{S}_{K\pi} = 0.15 \pm 0.24$, which is consistent with zero. We also select $B^0 \rightarrow D^-\pi^+$, $D^{*-}\pi^+$ and $D^-\rho^+$ candidates using the same event shape criteria. Neither mixing-induced nor direct CP -violating asymmetry is observed as expected. As an additional test of the consistency of the background treatment, we add events from the $B^0 \rightarrow \pi^+\pi^-$ sideband and adjust their ΔE and M_{bc} values. A fit to this background-enriched control sample, which has a background fraction comparable to the $B^0 \rightarrow \pi^+\pi^-$ sample, yields $\mathcal{S} = 0.08 \pm 0.06$ and $\mathcal{A} = 0.03 \pm 0.04$, both consistent with a null asymmetry.

We determine the statistical significance from the likelihood function, taking into account the boundary of the physical region as well as the effect of the systematic error. The Feldman-Cousins frequentist approach [14] gives a 99.6% confidence level (C.L.) for $-1 \leq \mathcal{S}_{\pi\pi} < 0$, equivalent to a 2.9σ significance for a Gaussian error. A similar analysis yields a significance of 2.9σ for $0 < \mathcal{A}_{\pi\pi} \leq 1$. The 95% C.L. intervals are found to be $-1.00 \leq \mathcal{S}_{\pi\pi} < -0.39$ and $+0.30 < \mathcal{A}_{\pi\pi} \leq +1.00$, respectively [15].

In summary, we have measured the CP violation parameters in $B^0 \rightarrow \pi^+\pi^-$ decay. Our result for $\mathcal{S}_{\pi\pi}$ indicates that mixing-induced CP violation is large. The large $\mathcal{A}_{\pi\pi}$ term is an indication of direct CP violation in B meson decay, and suggests that there is a large hadronic phase and interference between the tree and penguin amplitudes [16]. In this case the precise determination of $\sin 2\phi_2$ from $\mathcal{S}_{\pi\pi}$ requires additional measurements including the branching fractions for the decays $B^0 \rightarrow \pi^0\pi^0$ [17].

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